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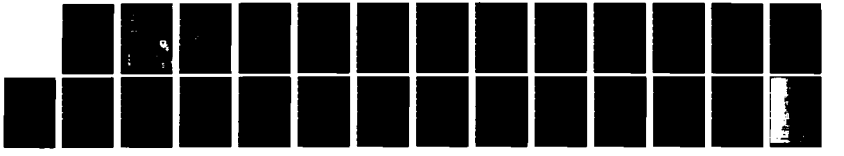

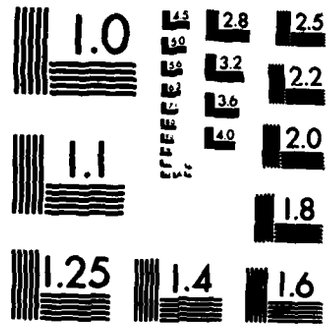

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General Guidelines for the Mitigation of Nuclear Weapon Effects on Fiber Optic Communication Systems through the use of Selected Design Practices

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This report provides guidelines for the design and installation of a fiber optic communication system to improve the tolerance of that system to a nuclear environment. These guidelines, if incorporated, can protect a significant portion of the national fiber optic communication system resources that might otherwise be destroyed.

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1. PURPOSE

This report provides guidelines to improve the tolerance of a fiber optic communications system (FOCS) to a nuclear environment. These guidelines, if incorporated, can protect a significant part of the national FOCS resources that otherwise might be destroyed.

2. BACKGROUND

A fiber optic communication system consists of a transmitter, receiver, repeater, network of fiber optic cables, and the power that is needed for the system to operate. Some or all of these components may be mounted above or below ground. The hostile nuclear weapon environments include blast and shock, thermal radiation, initial radiation, residual radiation, and electromagnetic pulse (EMP). All these environments can be expected within a localized region of space surrounding a surface or an atmospheric nuclear burst. For a nuclear burst above the earth's atmosphere (exoatmospheric or high altitude), only the EMP effect will be hostile to ground-based FOCS. Before we discuss the specific measures that can be designed to protect FOCS from these nuclear environments, it is wise to first discuss the environments themselves.

2.1 Electromagnetic Pulse Effect

Surface and air nuclear bursts threaten ground-based FOCS through a number of effects, one of which is EMP; high-altitude nuclear bursts are a threat only because of EMP. Guidelines for protection from EMP are included in section 3 of this report. There are basic differences between the EMP effect from a high-altitude nuclear burst and that from a surface or low-altitude nuclear burst. The high-altitude EMP will cover large areas of the U.S. from a single event; low-altitude EMP will affect only equipment in the immediate vicinity of the burst. Of course, high-level transients generated close to a low-altitude burst will propagate down power lines and other conductors and will need to be dealt with at greater distances than those associated with the source region.

Accompanying the low-altitude and surface burst EMP will be initial radiation, which can cause its own EMP within metal enclosures, and time-varying air conductivity, which will change the EMP coupling to conductors by providing an additional current driver that is proportional to the level of conductivity times the level of the incident electric field. There are other important differences between EMP effects at varying altitudes. For example, the EMP field close to a nuclear event will not be planar in nature and will not behave like a far-field EMP. Also, although EMP from the low-altitude and surface burst exists over a relatively small area, the energy contained in the pulse is usually much greater. The peak amplitude of the E field (except very

close in to the burst) is about the same for both, but the pulse width due to the low-altitude EMP may be 1000 times longer. Because of these differences and because of the difficulty in analyzing and simulating the low-altitude EMP effects there remain many questions regarding the effectiveness of EMP hardening practices required to protect systems close to a low-altitude event. Nonetheless, the practices recommended for high-altitude EMP hardening will also provide a great deal of protection for low-altitude EMP problems. The brief specific guidance in section 4.2 is included as a reminder of the EMP problem and is intended to recall the more detailed guidance in section 3.

2.2 Blast/Shock, Initial Radiation, Residual Radiation, and Thermal Effect

In low-altitude and surface detonations of nuclear devices, all the effects previously described are of potential concern. Factors such as the warhead yield, type, and height of burst will determine the magnitude of each effect.

The effect of each of these environments depends on the specific design, installation, and component selection of the FOCS. Because of this, it is not possible to say, except in very general terms, the relative significance of each environment. Such significance is important, however, from a hardening philosophy standpoint, since it would make little sense to harden a specific system to withstand blast overpressure consistent with a 1-MT surface burst at a distance of 16 km (10 mi) only to find that higher level residual radiation resulted in permanent darkening of all fiber links to a distance of hundreds of miles from the burst. A directed hardening effort would try to establish hardening consistency (balanced hardening) for all effects so that if a FOCS failed due to a specific nuclear environment, it would be close to failing from the other environments as well. As an example, consider the effects of a 1-MT fission-type nuclear weapon on a few examples of FOCS deployments.

Glasstone[1] identifies the magnitude of the effects of a 1-MT nuclear weapon (exclusive of the EMP effect).

2.3 Above-Ground Equipment, Above-Ground Fiber Optics--Height of Burst to Maximize Blast and Shock

If the FOCS is configured so that the transmitter and receiver are mounted in typical buildings, and if the repeaters and fiber optic links are mounted on telephone poles, then the predicted blast and shock effects would produce significant system destruction out to a radius of about 8000 m (5 mi). At 8000 m from the burst, a total initial radiation dose of less than 1 rad with a rate of 10^7 rads/s would be expected. Neither 1 rad of initial radiation nor a dose rate of 10^7 rads/s would be expected to do significant

[1] *Samuel Glasstone, The Effects of Nuclear Weapons, published jointly by the Department of Defense and the Department of Energy, Washington, DC (1977).*

permanent damage to a typical FOCS. However, a low yield weapon (e.g., 150 kT) would result in a dose rate of 2×10^9 rads/s at the same blast overpressure. This dose rate is enough to permanently damage FOCS electronics.

2.4 Above-Ground Equipment, Above-Ground Fiber Optic Cable--Height of Burst to Maximize Fallout (Surface Burst)

The fallout from a 1-MT surface burst is a function of time, distance, weather conditions, and wind. At 161,000 m (100 mi) downwind from the burst, a total radiation dose of 30,000 rads within the first 6 hr would not be unreasonable. This level of radiation is enough to permanently darken exposed optic fibers.* Its effect on system performance will depend upon the safety margin built into the system design. For above-ground systems this is potentially the most serious threat in terms of both range and extent of damage.

Thermal radiation from a 1-MT atmospheric burst would deliver about 30 cal/cm^2 at 8000 m (5 mi). At this range, some damage to the fiber optic cable covers would be expected, but it is unlikely that this damage would result in signal degradation.

The source-region (low-altitude, surface burst) EMP should be considered significant to a radius of 8000 m. At this range, the E field is primarily vertically polarized and slowly rising and would probably couple less to vertical conductors than would the vertically polarized, fast-rising, high-altitude EMP environment.

It can be seen that within 8000 m of a 1-MT fission-type detonation, above-ground FOCS can be damaged by blast/shock, EMP, and to some extent thermal environments.

Potentially more serious is the threat to FOCS from residual radiation which can extend downwind of the burst for a hundred miles or more.

2.5 Buried Fiber Optics with Above-Ground Transmitters, Repeaters, and Office Equipment†

The fiber optic links are assumed to be buried to a depth of 1 m below the earth's surface.

Damage from the blast and shock (optimized height of burst) would most likely be contained within 5000 m (3 mi) of ground zero.

The attenuation of gamma rays through 1 m of earth is about 1000. At 5000 m, the initial radiation dose is about 5 rads. Thus, at 3 mi the initial

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**This level is also enough to permanently damage the electronics of FOCS.*

†It is more realistic to assume that transmitters/receivers and office equipment are above ground than to assume a completely buried system.

radiation dose from a 1-MT burst through 1 m of earth would be no more than 1/200 rad. The dose rate at this range is about 5×10^8 rads/s, and at 1-m depth the dose rate would be reduced to about 5×10^5 rads/s. Above-ground electronics (especially in the repeater circuit) can sustain permanent damage and/or "latch-up" at dose rates of 5×10^8 rads/s.

It is unlikely that the buried fibers would be permanently darkened due to these levels. However, the exposed fibers exiting the ground would probably suffer permanent darkening to some extent. Also, the electronics exposed to these levels would be susceptible to damage. The overall effect on the FOCS would be system-dependent.

Downwind of the 1-MT surface burst, a total dose of residual radiation of 30,000 rads is possible at a range of 161,000 m (100 mi). For buried fibers, the level of exposure would be 30 rads. This is probably enough to permanently darken the fiber. As before, the portions of the fiber which exit the ground to go to repeaters and office equipment could suffer appreciable darkening and the electronics in above-ground installations could suffer permanent damage. Together, these effects could cause transmission problems over rather long sections of FOCS.

Also, the shallow burying of conductors will not add significant protection against EMP. Thus, if the buried fiber optics contain conductors--such as order wires or power wires--these conductors will be strongly excited by the horizontal EMP from an exoatmospheric burst. Possible damage will depend on hardening features incorporated in the design and the sensitivity of the specific electronics.

3. EMP GUIDELINE

Transient upset is not a consideration for the purposes of this report; therefore, the object is to minimize damage to the system.

High-altitude, low-altitude, and surface nuclear bursts will generate an EMP that will be coupled to power lines feeding repeaters, and other electronic components of the FOCS, as well as to any metallic strength members, metallic shields, and copper pairs that are incorporated into the optical fiber cable itself.

Although the EMP fields in the air are greater than the fields in the earth (for the higher frequencies of interest), the fields in the earth within a few meters of the air/earth interface are large enough to be of significant consequence. Therefore, buried cables should not be considered hard to EMP effects. This is true for both high-altitude and low-altitude nuclear events or for surface nuclear events.

Sections 3.1 and 3.4 have been extracted from a Naval Ocean System Center report.[2] Section 3.2 has been extracted from Harry Diamond Laboratories HDL-SR-82-2.[3]

Over the years, a number of engineering design practices have been developed to protect ground systems from EMP.[4-6] The basic protection philosophy behind the design practices is that they minimize, to as high a degree as possible, the propagation of external incident energy into sensitive electronics in enclosure interiors. Four generic categories of design practices are (1) reduction of interaction area or volume (EMP coupling reduction), (2) shielding and grounding, (3) protection of zone interface, and (4) designing for tolerance to transients. Since we are concerned here with reconstituting a system after an event, the fourth category--designing for tolerance to transients--will not be discussed.

3.1 Reduction of Interaction Area

The amount of energy coupled onto conducting system elements exposed to EMP is approximately proportional to their length and to the area these elements make in combination with the surrounding ground planes. The ground plane is typically defined by the earth itself for external conductors. This design practice category seeks to minimize the length or area of the conducting elements. Simple geometrical rearrangement of the facility during design can often result in fewer or shorter cable runs and in less favorable coupling geometries for wire-to-wire coupling and EMP field coupling. Running conductors next to ground planes minimizes pickup loops. The use of twisted pair cables, along with balanced sending and receiving circuits, can result in a cancellation of EMP-induced common transients. The EMP energy may be prevented from coupling into facilities by replacement of conducting structures with nonconductors and by substitution of optic links for communication cable elements.

3.2 Zonal Philosophy

Communication facilities (see fig. 1) contain several regions of electromagnetic environment separated by barriers such as building walls and cabinet shields. For example, the building walls separate the harsh external environment from the less harsh room environment, and the equipment cabinet separates the room environment from the small-signal environment inside the cabinet. Within the cabinet, there may be a third level of shielding to

[2] *EMP Engineering and Design Principles, Bell Laboratories (1975).*

[3] *P. R. Tryhus, Ground Based Systems EMP Design Handbook, MRCH/2-M-211, Mission Research Corporation (August 1977).*

[4] *EMP Engineering Practices Handbook, SRI, NATO File No. 1460-2 (October 1977).*

[5] *R. A. Greenwall, EMP Hardening of Tactical Ground Systems Through Electro-Optical Techniques: Design Guidelines, Naval Ocean System Center Technical Report 645 (20 December 1980).*

[6] *J. R. Miletta et al, Defense Switched Network Design Practices for Protection Against High-Altitude Electromagnetic Pulse, Harry Diamond Laboratories HDL-SR-82-2 (July 1982).*

separate the ambient small-signal environment from particularly sensitive component parts such as rf amplifier input stages or other low-noise stages. One can construct a shielding and grounding topology such as that illustrated in figure 2, where these natural shielded regions are represented by equipotential zones separated by electromagnetic barriers (shields).

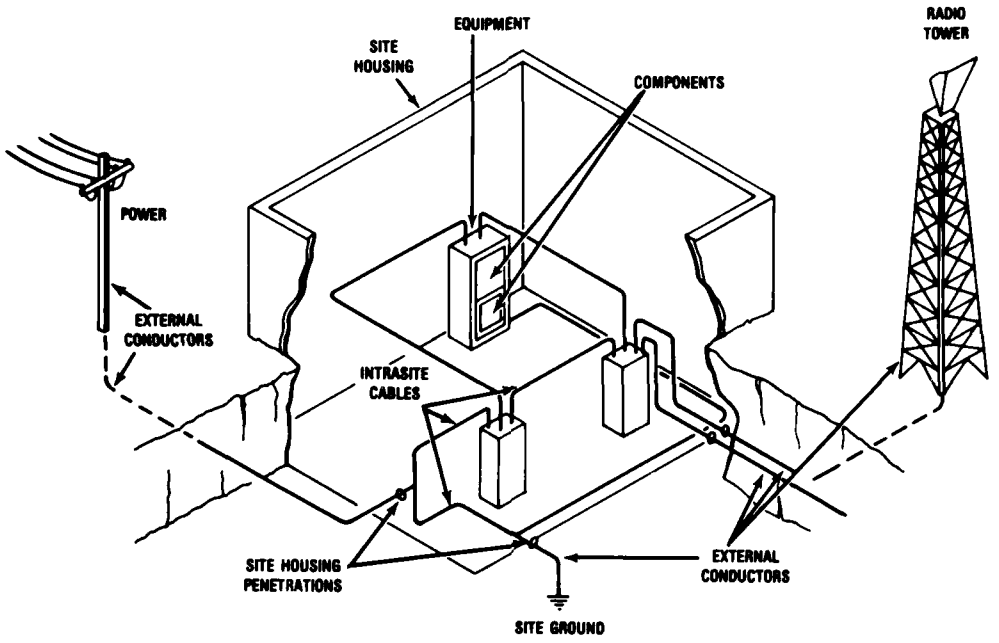

Figure 1. Typical defense switched network facility.

In buildings, the external environment (zone 0) is separated from the internal intrasite environment (zone 1) by the building's metallic structure (shield 1). One can then proceed to the cabinet walls (shield 2) and the cabinet environment (zone 2, etc.) to construct the shielding topology illustrated in figure 2. In this topology, the more interference-free pieces of equipment are identified by larger zone numbers and have a greater number of shields between them and the external environment. Ideally, the shields are continuous, closed, and highly conducting Faraday shields; in practice, they may be compromised by penetrating conductors (penetrators) or apertures. For example, an insulated conductor penetrating shield 1 will carry a large zone 0 current through the shield into zone 1 unless the conductor is treated with limiters and filters at the penetration point, as illustrated in figure 2. Similar violations of the zone barriers may occur between higher order zones. Thus, a conductor entering a cabinet may carry intrasite-level (zone 1) interference into the small-signal (zone 2) circuits unless interference-limiting procedures are applied at the cabinet entry point.

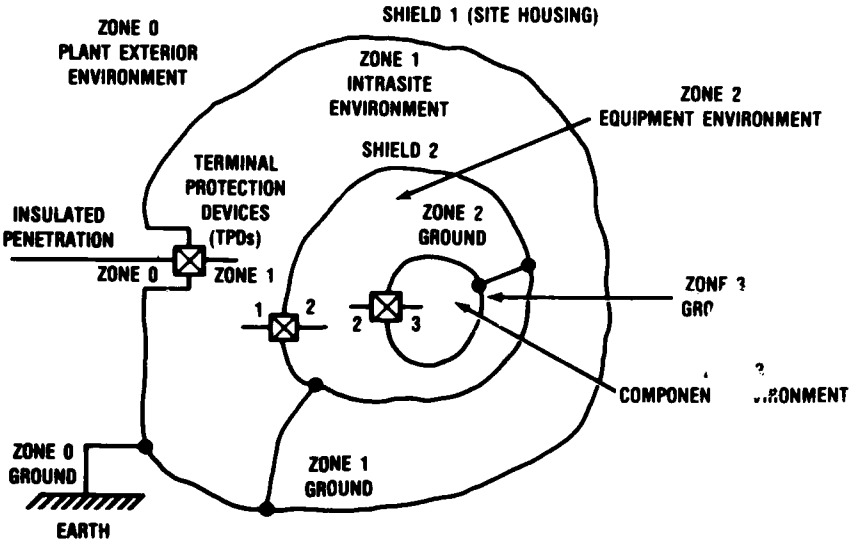

Figure 2. Environmental zones in complex facility.

3.3 Application of Zonal Philosophy

EMP design practices are developed in a zonal manner (e.g., fig. 1 and 2). The practical aspects of communication facility design coupled with equipment and component characteristics result in a familiar delineation of zone regions and boundaries. The regions and boundaries are, typically, characterized into five functional elements. These elements and their relationship to the zone boundaries are as follows:

(1) Components (zone 2/3 boundary and zone 3),
(2) Equipment (zone 1/2 boundary and zone 2),
(3) Intrasite, in plant, (zone 1),
(4) Site housing (zone 0/1 boundary), and
(5) Plant exterior (zone 0).

The numerical order indicates relative importance.

3.4 Design Practice for Achieving Zonal Protection

The following sections describe design practices to protect at the zone level.

Package Shielding.--For common shielding materials, such as steel, aluminum, and copper, a closed shield a few millimeters thick can reduce the ambient external field by 100 dB inside the shield. Cans, boxes, vans, or

other shielding enclosures take many forms. The ideal, continuously welded enclosure is almost never used because the equipment and personnel enclosed become inaccessible. In practice, the performance of a real shield is usually not governed by the thickness, permeability, or conductivity of materials (as these are usually sufficient), but rather by the defects that exist in the shield. These defects include the presence of minute apertures arising from construction, or large apertures, such as vents, doors, and seams, as well as various types of penetration (e.g., cables and pipes through the shield). Various techniques for maintaining shielding integrity are needed because of these obviously necessary penetrations.

The mechanical assembly of a shield must specify clean metal-to-metal mating surfaces. Good contact between the surfaces should be assured by the use of either a continuous bond or, at least, set screws or rivets at close intervals. The maximum allowable distance between fasteners is 2 to 4 in. (~50 to ~100 mm). Many metallic oxides, particularly aluminum oxide, are nonconductive. In addition, the finishes commonly applied to metals, such as the iridite or anodizing applied to aluminum or the cadmium plating applied to iron and steel, are less conductive than the metals themselves. Care should be taken to assure that a clean, highly conductive surface exists and can be maintained at each metal-to-metal contact point.

When openings are necessary for airflow, various forms of screens should be used to break the large opening into a series of small openings which act as waveguides below cutoff. To be most effective, the intersections between openings must be fused. Three commonly used devices are honeycomb, perforated sheet metal, and wire mesh screen. Honeycomb is usually the most effective for large openings and offers the additional advantage of low resistance to airflow. Wire mesh screen is useful when an opening requires shielding, yet visibility through the aperture must be maintained. The wire mesh is also useful for some shielding of vent holes that are too small to accommodate a honeycomb shield.

Openings which require visibility are often part of display devices, such as meters, display screens, lamps, etc. Large display apertures required for oscilloscope screens or plasma display panels generally need special shielding. At times it is necessary to use see-through wire mesh screens in front of the display panel in conjunction with a solid metal shield behind the panel.

To allow for servicing, most shielding equipment has a bolted cover of some kind. Spacing between fasteners must be closer for materials with thinner covers, because the mated surfaces buckle between the fasteners. For EMP shielding protection, gasketing ensures metallic contact. Any one of several types of conductive gaskets may be used to close the opening, but it must be thick enough and soft enough to fill in all irregularities. Where covers are to be removed and replaced, the gasket must be able to return to its original shape, or a new gasket must be used. The contact pressure should be high enough to make adequate contact, even when there is a nonconducting corrosion present. In most cases, any of a number of gasketing materials will electrically satisfy the requirements. However, EMP shielding must be

maintained during equipment use. Thus, it is important for the designer to consider mechanical suitability in specifying the overall EMP hardness.

Some shielded openings, such as doorways and hatches, are frequently opened and closed. In these cases, compression-type gasketing often is not satisfactory. An alternative gasketing arrangement is conductive finger stock, which affords a self-cleaning metal-to-metal seal between the doorway and the enclosure. The finger stock must be springy so that good mechanical contact is maintained throughout use. A beryllium copper alloy is often used to combine good spring action with high conductivity.

Conductive paints or epoxies can sometimes be used when shielding is not very critical. Their use for EMP shielding is very limited because their volume resistivities are usually on the order of 1000 times higher than copper, greatly limiting the amount of shielding available. Another great disadvantage is that most of the best conductive paints must be baked at over 1000 C to get the best electrical characteristics. Baking the enclosure is obviously not feasible because of the electronic gear inside.

Rectangular structures usually are approximated by cylinders, spheres, or parallel plate enclosures to solve shielding problems, if it is recognized that the solutions are inaccurate in near corners. The time dependence of the interior field is not changed, but the amplitude of the field can increase significantly at a corner. In the corners of rectangular boxes there is a concentration of current, which causes a larger magnetic field than predicted by spherical models. The field will double at $r = (0.25)X_0$, where X_0 is half of the longest box dimension and r is the distance from the corner. This buildup continues as the corner is approached and will be 10 times at $r = (0.06)X_0$. Thus, it is important to avoid placing magnetically sensitive devices or potential loop antennas near box corners. Rounding the corner is a useful preventive technique. Apertures and other discontinuities in the solid shell are also regions of locally high fields.

Cable Shielding.--Overall shields must be placed on cable which might be directly exposed to EMP or internal EMP (IEMP). It is useless to close apertures in package walls if transients are then allowed to flow freely on penetrating cables. The best cable shields are solid materials, such as rigid conduit or pipe. Such shields should be used where the weight and/or assembly penalty is not excessive. Doubled braided shields can be highly acceptable shielding for cables if the layers of braid are of the right weave, are of good conductivity, and are separated by a dielectric layer. The jacket is usually insulated and minimally affects the shielding properties of the cable. Unlike a solid shield, a braided shield offers many tiny apertures for electromagnetic coupling to the interior signal wires.

The signals induced on sensitive signal wires can be further reduced if the wires are shielded individually and placed in the center of the core bundle with low-impedance lines (e.g., power ground, etc.) on the periphery of the core bundle. Cable constructions such as this effectively have four levels of shielding. As with package shields, the continuity of shields must be maintained at the back shells of interface connectors. In particular, the

overall shield(s) must have circumferentially complete termination to the connectors. Pigtail terminations do not provide acceptable continuity. Special radio frequency interference/electromagnetic interference (rfi/emi) protective connector back shells should be used where possible.

Grounding.--Proper ground schemes help reduce system vulnerabilities to transient ground currents and maintain overall shielding integrity. It is often difficult to separate the subjects of shielding and grounding. In practice, several levels of shielding and grounding may be used. The system for facilities and equipment consists of two distinct elements: exterior grounding and zone grounding. The exterior ground attempts, in a field-significant way, to connect to the large, but poot, conductor which covers the earth's surface. This ground is particularly important, since it serves as a sink to which shield and penetration currents are diverted. The external ground should have a low impedance and should be distributed for easy connection and minimal earth gradients across the facility. The ring ground meets all these requirements and is a counterpart of the zone grounding, discussed next. Zone grounding often consists of a building or overall enclosure shield with its internal electrical grounding system, a cabinet shield with its internal electronics grounding system, and, perhaps, shielded components within the cabinet.

At each level the shield guards against the external environment, and the grounding controls potentials from internal sources.

The equipotential region within zones can be disturbed by internal sources or charge displacements. Thus, all older sources and internal conductors and structures, such as equipment enclosures, cable trays, shields, and conduits that are not intentionally at a potential different from the shield potential, should be connected to each other and to the inside surface of the shield. This common "grounding" approach, which includes even the outside of the shield enclosing the next inward zone, is used for each facility zone. This grounding scheme is known as regional single-point zone grounding and results in an overall internal ground tree.

An important rule of effective shielding and grounding practice is that topologically grounding conductors should never penetrate shield surfaces.

Inherent in the theory of electrodynamic shields is the fact that current in conductors attached to a shield flows predominantly on the surface to which the conductor is attached. This phenomenon is a manifestation of the skin effect in conductors. The skin effect permits currents on conductors outside the shield to be diverted to the outside surface of the shield.

Figure 3 shows several examples of correctly applied shielding, along with some common violations of correct shielding practice. Each of those violations permits the harsh currents on the outside conductors to flow into the protected zone shield. Filters and surge arrestors behave like any other connection of a penetration to the shield; that is, they divert harsh

interference currents to the outside surface of the shield, thereby preventing these currents from entering the protected region. Because power and signal carrying conductors cannot be continuously connected to the shield, they must be connected momentarily (when a certain threshold is exceeded) or connected only at frequencies not used for power or signals (i.e., through a filter). In any case, the diverted interference currents must flow to the outside surface of the shield, as illustrated in figure 3(c), if shield integrity is to be preserved.

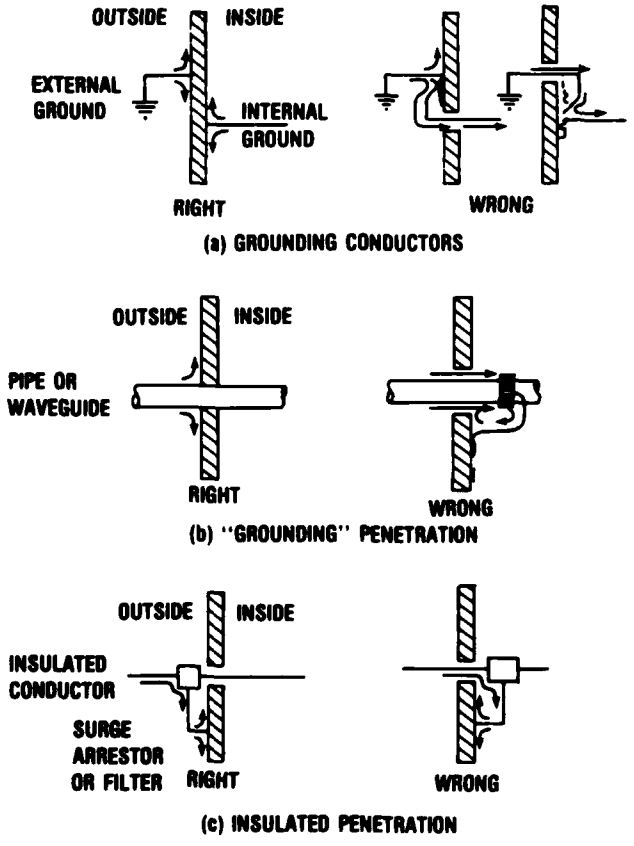

Figure 3. Connections that preserve shielding integrity (right) and compromise the shield (wrong).

Interface Protection.--Interface protection devices operate predominantly in one of two ways: by clamping (limiting the magnitude of currents or voltages) or by filtering (removing energy in certain frequency bands).

Practical clamping devices for EMP protection, which are generally placed in shunt with the input line, include varistors, diodes, and spark gaps. A clamping device appears to be a high-resistance shunt until the device threshold is reached, at which time the device becomes a low-impedance path and voltage is either clamped near the threshold point (varistor, diode) or drops to a lower value (spark gap). The V-I characteristics of the three types of clamping devices are shown in figure 4, and their characteristics are compared in table 1.

Spark gaps are useful for clamping the high level surges produced on external cables by EMP. However, their striking voltage is derivative dependent (dv/dt) due to the finite time required for arc formation. The spark gap will allow a large amplitude spike to pass through before clamping takes place.

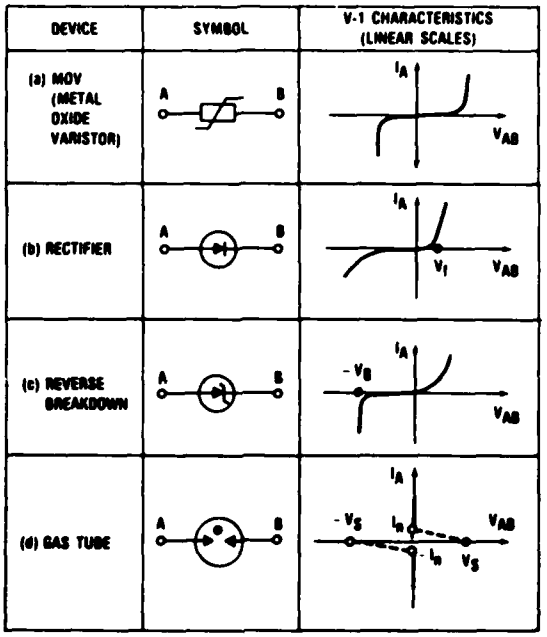

Figure 4. EMP clamping devices--V-I characteristics.

TABLE 1. COMPARISON OF PROTECTION DEVICES

Device type	Clamping (or filtering) thresholds	Operate time (s)	Highest burnout energy threshold (J)	Shunt capacitance (F)	Typical circuit applications	Possible disadvantages
Varistors						
Metal-oxide varistor	40 to 1500 V	$<10^{-9}$	$<10^{-3}$	10^{-9}	Power, af	High capacitance
Semiconductors						
Forward diodes	0.2 to 0.6 V	$<10^{-9}$	$<10^{1}$	10^{-12}	af, rf	Low burnout energy
Breakdown diodes	2 to 200 V	$<10^{-9}$	$<10^{2}$	10^{-8}	Power, af	High capacitance
Spark gaps						
High-speed gaps	550 to 20,000 V	$<10^{-9}$	$<10^{-3}$	10^{-3}	Term; af, rf	Power-follow, high cost
Arrestors using high-speed gaps	550 to 20,000 V	$<10^{-9}$	$<10^{3}$	10^{-11}	Power	High cost
Filters						
Ferrite chokes, beads	rf	-	-	-	Power, af	Ineffective protection, dc saturation
Feed-through capacitors	rf	-	-	-	Power, af	Dielectric breakdown
General RLC circuits	dc, af, rf	-	-	-	Power, af, rf	Impedance mismatching

Diodes work well as protective elements for semiconductors in many applications, but must be protected themselves if large surges are present.

Varistors are most often used for protection of ac line interfaces.

It is particularly important that clamping devices be properly installed so they will fullfill their protection capabilities. The protective elements should be mounted in a separate shielded enclosure as close to the input-output port as practical. Lead lengths of a protective device and its mounting should be minimized, to reduce the effects of clamp voltage increase due to lead resistance,

$$\Delta V_C = I_{EMP} R(\Omega/\ell)\ell \quad ,$$

and clamp voltage overshoot due to lead inductance,

$$\Delta V_C = L \frac{dI_{EMP}}{dt} \quad .$$

A filter suppresses certain frequency components from an EMP surge and can thus reduce energy allowed to pass to sensitive equipment inductors. Clamping devices operate only above a certain magnitude of surge voltage, but filters respond to specific frequency components regardless of magnitude. They can thus suppress spurious frequencies that might cause system upset, even if the interfering transient is not strong enough to activate a clamping device. For example, filters are very useful in protecting low-voltage digital circuits. Filters can also reduce the EMP wavefront slope, giving a slow spark gap time to respond.

Protective filters can be used only if the EMP surge energy does not have the same frequency components as the desired signal. For example, equipment terminating a dc power cable can be protected by a low-pass filter, which allows the desired low-frequency dc power through, but suppresses the high-frequency components of the EMP surge.

Devices that protect against transients must be rugged enough to withstand the transient and must be compatible with circuit operation. Consequently, each critical circuit must be analyzed separately before the best means for protection can be designed. Some of the most important considerations are the following: maximum operational voltage excursion, bandwidth or bit rate, circuit function, and the induced EMP waveform.

Each device described so far has a limited protective function and, by itself, may not protect equipment. Adequate protection sometimes requires a hybrid circuit, which has more than one type of device to compensate for deficiencies or to minimize possible side effects. A parallel spark gap and zener diode combination uses the zeners' subnanosecond response and low breakdown voltage to immediately clamp the transient surge to safe levels for the equipment to be protected. Then, several nanoseconds later, the spark gap fires and protects the zener from burnout caused by excessive power dissipation. A series spark gap and varistor combination uses the essentially open-circuit nature of the spark gap in its quiescent state for a high degree

of dc and ac isolation of the protective elements from the main circuit and then uses the varistor to ensure that the spark gap will turn off in a dc situation.

In EMP coupling to cables, the common mode transient often dominates the differential mode. Cabling practices such as the use of twisted pairs and balanced termination reduce the differential mode coupling. Interface hardening can then be augmented by circuit designs that suppress vulnerability and sensitivity to common mode signals.

3.5 Specific Guidance for EMP Protection of Fiber Optic Systems

There are many ways fiber optic systems can be protected:

(a) Install transmitter and receiver components in a high conductivity metal enclosure whose walls are thick enough to adequately assure EMP shielding and mechanical rigidity. The access cover should be as thick as the enclosure.

(b) Eliminate all enclosure apertures except those that are absolutely necessary, such as those for the fiber optics, for the seams of the access cover, and for the input/output (I/O) connectors.

(c) Place the power and data I/O lines in double braided shielded cable or in metal conduit that terminates at both ends with peripheral shields to high conductivity metallic enclosures. Route I/O lines to eliminate EMI coupling between power and signal lines.

(d) Provide transient suppression or filtering on all lines where shielding is insufficient to prevent damage. Adequate shielding may be impractical if power or data I/O lines are long and exposed to scattering-enhanced EMP fields.

(e) Use nonconductors, such as Kevlar or Aramid fibers, to strengthen fiber optic cables. Do not include metal conductor power or signal lines in the fiber optic cable.

(f) Use a high conductivity I/O connector with a conductive metal finish.

(g) Use a metal fiber optic connector or run the fiber through a small-diameter metallic tube that is peripherally attached to the enclosure and is long enough to attenuate the local exterior EMP field.

(h) Provide good electrical contact between the enclosure and access cover, with at least 0.50-in. (12.7 mm) mating surfaces or lips. The mating surfaces should be tin plated, for a noncorrosive finish. The access cover should be attached with screws spaced 2 in. (50.8 mm) apart and torqued to 50 in.-lb. Nutplates and fast release fasteners must not be used.

(i) Use an emi gasket in mating the access cover to the enclosure. The gasket should be metal mesh, metal spiral, or wire-filled rubber. If the above guidelines are used to package the link components, the link can be protected against upset and component damage. Use similar guidelines to harden the system elements that provide the I/O signal and the power to the fiber optic links.

(j) Use local battery uninterruptible power supplies where possible. Systems that are directly run from batteries are to some degree isolated from power line transients, although the batteries are constantly under charge.

4. GUIDELINES FOR LOW-ALTITUDE NUCLEAR ENVIRONMENTS

For the low altitude or surface burst, effects other than EMP predominate, and the object is to (1) minimize damage to the system through system design, component selection, system installation and hardening measures and (2) provide for the reconstitution of a reasonable system through standardization of various systems, subsystems, and interfaces and provision of interface points.

FOCS are designed to account for losses incurred in fibers, splices, optical coupling, and receiver sensitivity to achieve the maximum allowable repeater spacing with a sufficient design margin for proper operation over the normal environmental variations. Nuclear radiation effects are not considered in deriving the loss budget. Additional losses that occur due to radiation effects include increased fiber losses due to fiber darkening, reduced receiver sensitivity and increased receiver noise, and reduced emitter output. In addition to reducing the repeater spacing and providing more design margin, the following guidelines can be applied to reduce the nuclear susceptiblity of FOCS.

4.1 Initial Nuclear Radiation and Residual Radiation

The following guidelines should be implemented to protect FOCS during initial and residual radiation environments.

(a) Operate at long wavelengths (1.3 to 1.5 μm) and use Ge-doped silica core optical waveguides that do not contain phosphorus; operation at 1.5 μm is preferable over operation at 1.3 μm.

(b) Use photodetectors with no internal gain; that is, avoid the use of avalanche photodiodes (APD's). If APD's are used, keep internal gain to a minimum. Provide sufficient current limiting to the photodetector to prevent prompt-gamma-induced burnout. Photodetectors fabricated from III-V semiconductor material are preferred over those fabricated from Si or Ge.

(c) Insure that lasers do not overheat; for example, if air-conditioning in shelter stations fails, have an alternate cooling source.

(d) Avoid the use of N-channel metal oxide semiconductor (NMOS) devices in electronic equipment; assess the radiation hardness of other MOS devices before they are used in electronic equipment. Bipolar devices are preferable when used with well-established principles of circuit design and conservative design margins.

(e) Provide for automatic power removal to prevent latchup and/or burnout in circuits using MOS, bipolar, and other semiconductor devices (unijunction transistors, silicon-controlled rectifiers, etc.); reset manually or automatically. In lieu of the above, hard circuit components with current limiting designed into the circuits are required, but logic upset will still occur and reset is required (either automatic or manual).

(f) Bury fiber optic cable preferably at depths greater than 1 m (~ 3 ft); bury repeaters if possible.

(g) Provide for operation at a reduced data rate; also determine how information can be rerouted.

4.2 Electromagnetic Pulse

The following guidelines should be implemented to protect FOCS during the EMP environment.

(a) Avoid the use of metal members (e.g., strength members, core wraps, etc.) in fiber optic cable; use nonmetallic materials in fiber optic cable whenever possible. If metal members are used, establish a grounding scheme for metal members of fiber optic cable, but take care to avoid EMP-induced current in ground loops.

(b) Put terminal protection devices (TPD's) on repeater power inputs (from local power).

4.3 System-Generated Electromagnetic Pulse

The following guidelines should be implemented to protect FOCS during the system-generated (SGEMP) environment.

Use shielded cables (with rf shielding effectiveness of at least 30 dB) for power cables, signal interconnects, etc., to minimize the effects of SGEMP, and ground all cable penetrations to cabinets; also, ground all cabinets. Use TPD's for long cable runs.

4.4 Blast

The following guidelines should be implemented to protect FOCS during the blast environment.

Avoid the use of thin-walled mobile buildings for shelters. Solid fixed-site structures (e.g., reinforced concrete, reinforced masonry block,

etc.) are recommended for exposed repeater stations and terminals. Keep openings in buildings as small as possible. Locate entry and exit ports for cables, etc., on the side of the repeater station that is opposite the expected or likely ground zero (e.g., industrial target) whenever possible; run cables radially away from probable ground zero. Allow rattle space (sufficient intervening space) between walls of repeater stations and equipment in the station. Provide for easy maintenance and rapid replacement for fiber optic cables installed on utility poles.

4.5 Thermal Radiation

The following guidelines should be implemented to harden FOCS during the thermal environment.

Avoid the use of plastics, thin metal components, and flammable materials that may be exposed to intense thermal radiation. Locate cable, components, etc., in positions that are shielded from direct thermal exposure whenever possible. Covering the cable (not burying) with a few inches of earth significantly reduces thermal damage. If fiber optic cables are exposed, they should be covered with a thick flame-resistant outer jacket (e.g., 2-mm thick flame-resistant rubber or PVC--polyvinyl chloride for buried installations with above-ground terminations and 1-mm thick for above-ground installations carried on utility poles).

4.6 Implementing Guidelines

All the guidelines in section 4, except 4.1a and b, can be achieved by the use of selected commercially available devices and materials, by following accepted nuclear weapon effects hardening procedures, or by instituting operational modifications to the fiber optic system. Guideline 4.1a specifies a fiber composition (Ge-doped silica core optical waveguide that does not contain phosphorus) that research has shown to be a mitigation technique, but commercial availability is not known. Likewise, the commercial availability of III-V photodetectors (refer to guideline 4.1b) that are suitable for some proposed FOCS operations is not known.

5. SUMMARY

The guidelines suggested in this report should be given serious consideration when FOCS is being designed and installed. If the guidelines are incorporated, they can protect a significant part of the national FOCS resources that might otherwise be rendered inoperable directly following and for some considerable period of time after a nuclear attack.

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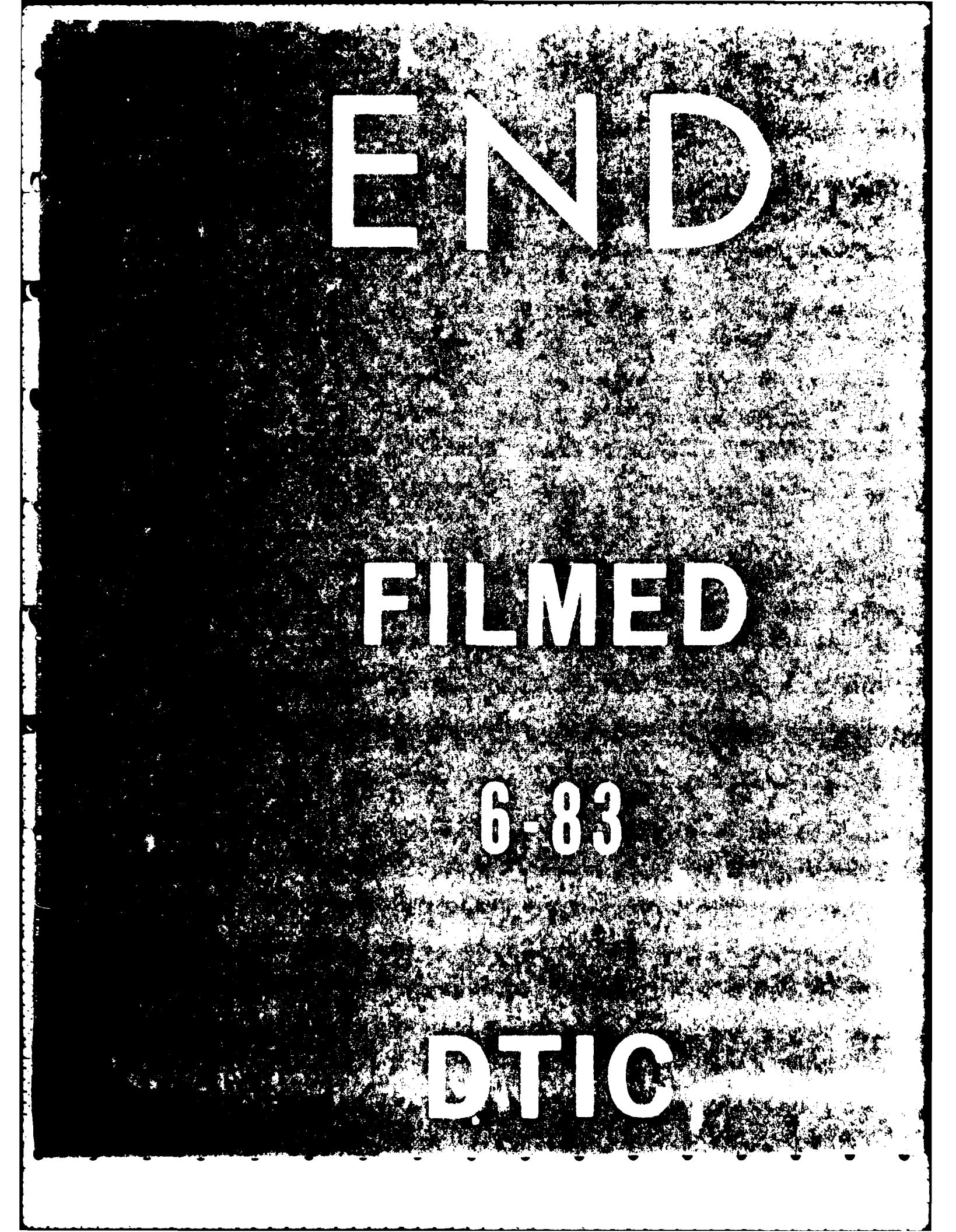
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